CUORICINO: final results

Sergio Di Domizio on behalf of the CUORICINO collaboration

University and INFN - Genova

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CUORICINO was a bolometric experiment for the search of neutrinoless double beta decay (DBD) in $^{130}\text{Te}$

- Detector description
- Results for $^{130}\text{Te}$ neutrinoless DBD to the ground state
- Results for $^{130}\text{Te}$ DBD to the first excited state $0^+$ of $^{130}\text{Xe}$
- Results for $\beta^+/\text{EC}$ DBD of $^{120}\text{Te}$
- Study of the muon-induced background in CUORICINO
- Feasibility of WIMP and solar Axion search in CUORE-0 and CUORE
**Bolometric technique**

**Working principle:** measure the temperature rise of the energy absorber

$$\Delta T = \frac{E}{C}$$

- **Heat bath ~ 10 mK** (copper)
- **Thermal coupling** (PTFE)
- **Thermistor** (NTD-Ge)
- **Absorber Crystal** (TeO$_2$)

**source ≡ detector**

**Typical parameters of the CUORICINO bolometers**

**Absorber crystal: TeO$_2$**
- $M = 790$ g
- $C = 2 \times 10^{-9}$ J/K
- $\Delta T = 0.1$ mK/MeV

**Sensor: NTD Ge thermistor**
- $R = R_0 \exp\left(\frac{T_0}{T}\right)^{1/2}$
- $R_0 = 1 \, \Omega, \, T_0 = 3 - 4 \, K$
- $R = 100 \, M\Omega$
- $\Delta R = 3 \, M\Omega/\text{MeV}, \, \Delta V = 0.3 \, \text{mV/MeV}$
Isotope choice: $^{130}\text{Te}$

- Q-value: $\sim 2527.5$ keV
- Isotopic abundance: 33.8%
- Favorable nuclear structure factor
- $\text{TeO}_2$ crystals have good thermal and mechanical properties

Q-value measurements:

- $2527.518(13)$ keV
- $2527.01(32)$ keV
- $2526.97(23)$ keV

References:

Detector

A tower of 62 TeO$_2$ crystals

- 11 floors made of 4 crystals
  - not enriched
  - Mass: 790g
  - Dimensions: 5x5x5 cm$^3$
- 2 floors made of 9 crystals:
  - Mass: 330g
  - Dimensions: 3x3x6 cm$^3$
  - 2 enriched in $^{128}$Te (82%)
  - 2 enriched in $^{130}$Te (75%)

Total mass: 40.7 Kg (11.3 Kg in $^{130}$Te)

Shieldings

**Internal:**

- 1cm low activity Pb
  - (A < 4 mBq/Kg in $^{210}$Pb)

**External:**

- 20cm Pb
- 20cm Borated Polyethylene
- Anti-Rn box: Nitrogen overpressure
Energy calibration

~3 days calibration performed about once per month by inserting $^{232}$Th sources between the cryostat and the external lead shields

Calibration error at $^{130}$Te $\beta\beta$ Q-value: $\pm 0.4$ keV
Cuoricino was located underground, in the Hall A of the Laboratori Nazionali del Gran Sasso (Italy) under a 3650 m w.e. shield against cosmic rays.

Data taking started in April 2003 and ended in June 2008. The data are separated in two runs (RUN I and RUN II), due to a major maintenance interruption.

Average energy resolution (big xtals): **6.3 keV**
Evaluated on the 2615 keV peak from $^{208}$Tl.

<table>
<thead>
<tr>
<th>Crystal Type</th>
<th>$&lt;\Delta E_{\text{FWHM}}&gt;\ (\text{keV})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$5 \times 5 \times 5 \ \text{cm}^3$</td>
<td>6.3±2.5 keV</td>
</tr>
<tr>
<td>$3 \times 3 \times 6 \ \text{cm}^3$ (natural)</td>
<td>9.9±4.2 keV</td>
</tr>
<tr>
<td>$3 \times 3 \times 6 \ \text{cm}^3$ (enriched)</td>
<td>13.9±5.3 keV</td>
</tr>
</tbody>
</table>
Bkg at Q-value: \(0.17 \text{ counts/(keV kg y)}\)

Statistics: \(19.75 \text{ kg}^{(130\text{Te})} \text{ y}\)

Maximum likelihood fit with 8 free parameters:
- \(0\nu\beta\beta\) rate
- 3 flat bkg rates (big, small and enriched xtals)
- 3 \(^{60}\text{Co}\) rates (big, small and enriched xtals)
- \(^{60}\text{Co}\) sum energy (same for all detectors)

\[
\Gamma^{0\nu} = ( -0.2 \pm 1.4 \text{ (stat)} \pm 0.3 \text{ (syst)} ) \times 10^{-25} \text{ y}^{-1}
\]

Half life limit: Bayesian approach with flat prior

\[
T^{0\nu}_{1/2} > 2.8 \times 10^{24} \text{ y} \quad @ \text{90\% CL}
\]

\(m_{\beta\beta}\) \< (300 – 570) meV \quad (R)QRPA
\< (360 – 580) meV \quad \text{pnQRPA}
\< (570 – 710) meV \quad \text{ISM}
\< 370 meV \quad \text{IBM-2}

The CUORICINO limit on \(m_{\beta\beta}\) is comparable with the one reported by the Heidelberg-Moscow experiment in \(^{76}\text{Ge}\), but can not exclude the claim of observation.
Background contributions at $Q_{\beta\beta}$

- $^{60}$Co from cosmogenic activation: negligible
- Multi-Compton from $^{208}$Tl ($^{232}$Th cont. in cryostat shields): ~40%
- Degraded alphas from crystal surfaces: ~10%
- Degraded alphas from Cu holders surfaces: ~50%
- Muon-induced background: negligible

Surface alpha contaminations produce a continuous spectrum that extends down to the $Q_{\beta\beta}$ region

The contributions of copper and crystal contaminations can be studied by comparing the single and double hit energy spectra

Tests performed in the Hall C R&D facility showed that the alpha background can be reduced by proper cleaning procedures. The crystal surface contribution is now under control, while the copper surface contribution is still a factor of 4 above the CUORE background goal ($10^{-2}$ counts/(keV kg y))
Decay accompanied by the emission of two $\gamma$'s: 1257 keV and 536 keV

The electrons (and neutrinos, in the 2$\nu$ decay mode) share a total energy of 734 keV

**Theoretical calculations:**

$0\nu$ ($m_{\beta\beta} = 1$ eV): $T_{1/2}^{0\nu} = 7.5 \times 10^{25}$ y

$2\nu$: $T_{1/2}^{2\nu} = (0.5 \div 1.4) \times 10^{23}$ y

**Coincidence-based analysis**

- Search for events involving two or three crystals
- Require that the photons are completely absorbed in one crystal
- Three possible scenarios:

  - Both $\gamma$'s escape the decay crystal
  - The 1257 keV $\gamma$ escapes. The 536 keV $\gamma$ is trapped in the decay crystal
  - The 536 keV $\gamma$ escapes. The 1257 keV $\gamma$ is trapped in the decay crystal

**Table**

<table>
<thead>
<tr>
<th>Signature [keV]</th>
<th>Decay</th>
<th>Efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>734 $\oplus$ 536 $\oplus$ 1257</td>
<td>0$\nu$</td>
<td>0.44 ± 0.02</td>
</tr>
<tr>
<td>1257 $\oplus$ 1270</td>
<td>0$\nu$</td>
<td>1.79 ± 0.04</td>
</tr>
<tr>
<td>536 $\oplus$ 1991</td>
<td>0$\nu$</td>
<td>1.10 ± 0.03</td>
</tr>
<tr>
<td>(0 – 734) $\oplus$ 536 $\oplus$ 1257</td>
<td>2$\nu$</td>
<td>0.41 ± 0.02</td>
</tr>
<tr>
<td>(536 – 1270) $\oplus$ 1257</td>
<td>2$\nu$</td>
<td>2.29 ± 0.05</td>
</tr>
<tr>
<td>(1257 – 1991) $\oplus$ 536</td>
<td>2$\nu$</td>
<td>1.00 ± 0.03</td>
</tr>
</tbody>
</table>

**Signal search** is performed on the hit highlighted in red in the above table.
Excited states: $0\nu$DBD

No evidence for a signal, background negligible

Use poisson posterior p.d.f. for zero observed events

Half life limit extracted with a Bayesian approach, assuming a flat prior

$$T_{1/2}^{0\nu} \left( ^{130}Te \rightarrow ^{130}Xe^* \right) > 9.4 \times 10^{23}\, \text{y} \quad @ \, 90\% \, CL$$

Limit improved by almost two orders of magnitude with respect to previous publications

arXiv:1108.4313
Excited states: $2\nu$DBD

Signal search performed using a ML unbinned fit

Half life limit extracted with a bayesian approach, assuming a flat prior

$$T_{1/2}^{2\nu}(^{130}Te \rightarrow ^{130}Xe^*) > 1.3 \times 10^{23} \text{ y} \quad @ \ 90\% \ CL$$

Limit improved by almost two orders of magnitude with respect to previous publications

[arXiv:1108.4313]
$^{120}\text{Te} \rightarrow^{120}\text{Sn} + e^+ (+2\nu)$

Q = (1714.8 ± 1.3) keV

**Theoretical calculations:**

- $0\nu$: not available
- $2\nu$: $T_{1/2}^{2\nu} = 4.4 \times 10^{26}$ y

Isotopic abundance: **0.096%**

Statistics: **0.0573 kg($^{120}\text{Te}$) y

**Analysis approach**

In the $0\nu$ decay mode, the energy transferred to the positron is $K_{\text{max}} = Q - 2 m_e c^2 - E_b$

If $E_b$ is contained in the detector, the total energy release is $E_0 = K_{\text{max}} + E_b = 692.8$ keV

In the $2\nu$ decay mode the kinetic energy of the positron has a continuous distribution between $E_b$ and $K_{\text{max}}$ ($E_b = 30.5$ keV if the capture proceeds through the K shell)

**Coincidence-based analysis:** search for events in coincidence with one or two 511 keV gammas (from positron annihilation)

<table>
<thead>
<tr>
<th></th>
<th>0ν</th>
<th>2ν</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>692.8 keV ⊕ 511 keV</td>
<td>(30.5 - 692.8) keV ⊕ 511 keV</td>
<td>3.40 ± 0.02 %</td>
</tr>
<tr>
<td></td>
<td>692.8 keV ⊕ 511 keV ⊕ 511 keV</td>
<td>(30.5 - 692.8) keV ⊕ 511 keV ⊕ 511 keV</td>
<td>0.45 ± 0.01 %</td>
</tr>
<tr>
<td></td>
<td>1203.8 keV ⊕ 511 keV</td>
<td>(541.5 - 1203.8 keV) ⊕ 511 keV</td>
<td>6.23 ± 0.03 %</td>
</tr>
</tbody>
</table>

Efficiencies evaluated using a GEANT4-based simulation
$^{120}\text{Te } \beta^+/\text{EC}: 0\nu\text{DBD}$

$0\nu: 511\text{ keV} + 1204\text{ keV}$

- DE of 2204 keV ($^{214}\text{Bi}$)
- SE of 1730 keV ($^{214}\text{Bi}$)

$0\nu: 511\text{ keV} + 511\text{ keV} + 693\text{ keV}$

- DE of 1764 keV ($^{214}\text{Bi}$)

Additional results:

- $T_{1/2}^{0\nu} > 1.9 \times 10^{21}$ y at 90% CL

- Limit improved by more than four orders of magnitude with respect to previous publications

\textbf{\textsuperscript{120}Te $\beta^+/EC$: 2$\nu$DBD}

For the 2$\nu$ analysis consider only the signature with the best signal to background ratio:

\[(30.5 - 693)\text{ keV} \oplus 511\text{ keV} \oplus 511\text{ keV}\]

\section*{Background sources}

\textbf{Physical coincidences:} remove events within $\pm 3\sigma$ around the DE peaks from known radioactive lines:
- 1120.3 keV and 1238.1 keV of $^{214}\text{Bi}$ (3)
- 1173.2 keV and 1332.5 keV of $^{60}\text{Co}$ (2)
- 1460.8 keV of $^{40}\text{K}$ (1) \rightarrow \textbf{8 events left}

\textbf{Random coincidences:} estimated looking at the spectra of events in triple coincidence with the side bands of the 511 keV peak: \textbf{4.3 events}

upper limit on the number of signal counts estimated using a Bayesian approach
Assume 4 bkg events over 8 observed events:

\[n_{SIG} < 9 \text{ @ 90\% CL}\]

\[T_{1/2}^{2\nu} > 0.9 \times 10^{20} \text{ yr} \text{ @ 90\% CL}\]

Limit improved by almost three orders of magnitude with respect to previous publications

\textit{Astropart.Phys. 34 (2011) 643-648}
Muon-induced background

A test with plastic scintillators surrounding the CUORICINO detector was performed in the last 3 months of data taking of the experiment.

Study the correlations between the bolometric signals and the triggers from the plastic scintillators.

The test showed that operating the bolometers in anti-coincidence is effective at eliminating potential muon-induced backgrounds.

Before anti-coincidence cuts

After anti-coincidence cuts

$BKG_{\mu}$ at 2530 keV $< 0.0021$ counts / (keV kg y) @ 95% CL

Low energy threshold trigger

New trigger algorithm: energy threshold down to few keV

Key concept: run the trigger on data processed with the optimum filter. Higher SNR ⇒ lower threshold

\[ H(\omega) = \frac{S^*(\omega)}{N(\omega)} e^{-i\omega t_m} \]

- average signal shape (estimated from data)
- maximum position
- noise power spectrum (estimated from data)

Detection efficiency

![Detection Efficiency Graph]

- standard trigger thresh. ~ 20 keV
- new trigger thresh. ~ 3 keV

Study performed on three test bolometers

The region of interest for WIMP and Axion interactions in TeO$_2$ is below 25 keV

The new trigger algorithm, with a threshold of few keV, opens the possibility to search for dark matter signals in CUORE-0 and CUORE

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Conclusions

- CUORICINO set the most sensitive limits on the half life of the following processes:
  - $^{130}\text{Te}$ neutrinoless double beta decay:
    \[ T_{1/2}^{0\nu}(^{130}\text{Te}) > 2.8 \times 10^{24} \, y \text{, } 90\% \text{ CL} \]
  - $^{130}\text{Te}$ double beta decay to the first excited state $0^+$ of $^{130}\text{Xe}$:
    \[ T_{1/2}^{0\nu}(^{130}\text{Te} \rightarrow ^{130}\text{Xe}^*) > 9.4 \times 10^{23} \, y \text{, } 90\% \text{ CL} \]
    \[ T_{1/2}^{2\nu}(^{130}\text{Te} \rightarrow ^{130}\text{Xe}^*) > 1.3 \times 10^{23} \, y \text{, } 90\% \text{ CL} \]
  - $^{120}\text{Te}$ $\beta^+/\text{EC}$ double beta decay:
    \[ T_{1/2}^{0\nu}(^{120}\text{Te}) > 1.9 \times 10^{21} \, y \text{, } 90\% \text{ CL} \]
    \[ T_{1/2}^{2\nu}(^{120}\text{Te}) > 0.9 \times 10^{20} \, y \text{, } 90\% \text{ CL} \]

- The muon-induced background was negligible

- The implementation of a low energy threshold trigger opens the possibility to perform dark matter searches in CUORE-0 and CUORE